Monitoring Sea Surface Processes Using the High Frequency Ambient Sound Field

Jeffrey A. Nystuen
Applied Physics Laboratory
University of Washington
1013 NE 40th Street
Seattle, WA 98105
phone: (206) 543-1343 fax: (206) 543-6785 email: nystuen@apl.washington.edu

Award #: N00014-04-1-099

LONG-TERM GOAL

To make passive acoustic monitoring of the marine environment an accepted quantitative tool for measuring sea surface conditions (wind speed, rainfall and sea state), monitoring for the presence and identity of marine wildlife (especially whales), and monitoring anthropogenic activities including shipping, sonar and other industrial activities. By establishing a methodology for describing the sound budget for a location, including the quasi-steady sound levels from the sea surface and the frequency and intensity of transient sounds from marine wildlife and human activities (close and distant shipping, sonar activities, other acoustic "beacons", etc.), a baseline of information for making decisions regarding additional human activities, in particular Naval operations using active sonars, will become available. This decision aid is needed to understand the perceived affect of sound-producing activities, in particular, Naval operations and research activities, on the marine environment.

SCIENTIFIC OBJECTIVES

This research focuses on the frequency band from 1-50 kHz. In this frequency band the primary sound sources are the sea surface, including breaking waves and rainfall, and various transient sources, including marine wildlife and human sources (ships, sonars, etc.). Long term monitoring has demonstrated quantitative acoustic wind speed measurement for winds from 3-20 m/s and rainfall detection and measurement for rainfall rates from 2-200 mm/hr (Ma and Nystuen, 2005). The influence of wind on the signal from rainfall has been quantified, and an improved sound prediction model has just been published (Ma et al., 2005). The data sets examined so far are mostly from tropical deep-ocean moorings, which generally do not experience extremely harsh high wind and sea state conditions. Newly acquired data sets include some high latitude locations in the North Pacific and Bering Sea, where winds over 20 m/s are present. These data sets are being examined to extend the measurement algorithms to very high sea states. Is there an acoustic signature of "sea spray" in extreme conditions?

Ambient sound data sets also contain many examples of transient sounds. These have generally been treated as "noise" and are ignored in predictive models that use heavily smoothed and generic spectra. However, the frequency and character of these sounds are part of the sound budget for a location, and represent the signal for many types of studies, in particular, marine mammal population studies (Mellinger et al. 2004). A methodology for describing the sound budget of a particular location is being developed, including the frequency and character of these transient sounds. An objective methodology for detecting and identifying different sound sources depends on the unique

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Monitoring Sea Surface Processes Using the High Frequency Ambient Sound Field**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Applied Physics Laboratory,1013 N.E. 40th St.,Seattle,WA,98105**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

characteristics of each sound source. Such an objective analysis model needs to be applied to disparate data sets from tropical, mid-latitude, high-latitude, coastal and inland waterways to assess universal performance. These data sets are available for this research effort (Table 1).

TECHNICAL APPROACH

Passive Aquatic Listeners (PALs), previously called Acoustic Rain Gauges (ARGs), are autonomous acoustic recorders designed to be attached to ocean moorings. They consist of a broadband, low noise hydrophone, a signal processing board, a low-power microprocessor with a 100 kHz A/D digitizer, a memory card and a battery pack. The sampling strategy can be designed to allow autonomous operations for up to one year. Three generations of PALs have been designed and built at the Applied Physics Laboratory. Over 100 buoy-months of data have been collected from deep ocean, continental shelf and coastal ocean moorings (Table 1). Recently PALs have been adapted for marine mammal monitoring including a capacity to record a limited number of short time series. These short time series will contribute to the identification of sound sources.

Table 1. Locations and times of PAL deployments

Location	depth	Period	Notes
8°N, 95°W	38m	1999-2004	ITCZ of Eastern Tropical Pacific Ocean
10°N, 95°W	38m	1999-2004	ITCZ of Eastern Tropical Pacific Ocean
12°N, 95°W	38m	1999-2004	ITCZ of Eastern Tropical Pacific Ocean
0°, 165°E	20-98m	2000-2002	Warm pool of the Western Tropical Pacific Ocean
20°S, 80°E	50 m	2001-2003	Stratus deck region of Eastern Pacific Ocean
Bering Sea	20 m	2004	High latitude coastal shelf, very little shipping
Haro Strait	100 m	2004, 2005	Inland waterway with heavy shipping traffic
Carr Inlet	10 m	2003	Inland waterway with minimal shipping traffic
50ºN,145ºW	50 m	2004-2005	North Pacific Ocean
Cape Flattery	50 m	2005, 2006	Coastal Shelf, shipping and mammals present

Physically a PAL is a cylindrical instrument 30 inches long by 6 inches in diameter. The hydrophone extends from one end. It is typically mounted in a cage to avoid damage by possible fishing lines. The weight in water is about 10 lbs, making it deployable on almost any type of mooring line. New casings are more robust and will increase the weight to about 20 lbs in water and allow deployment depths of up to 2000 meters.

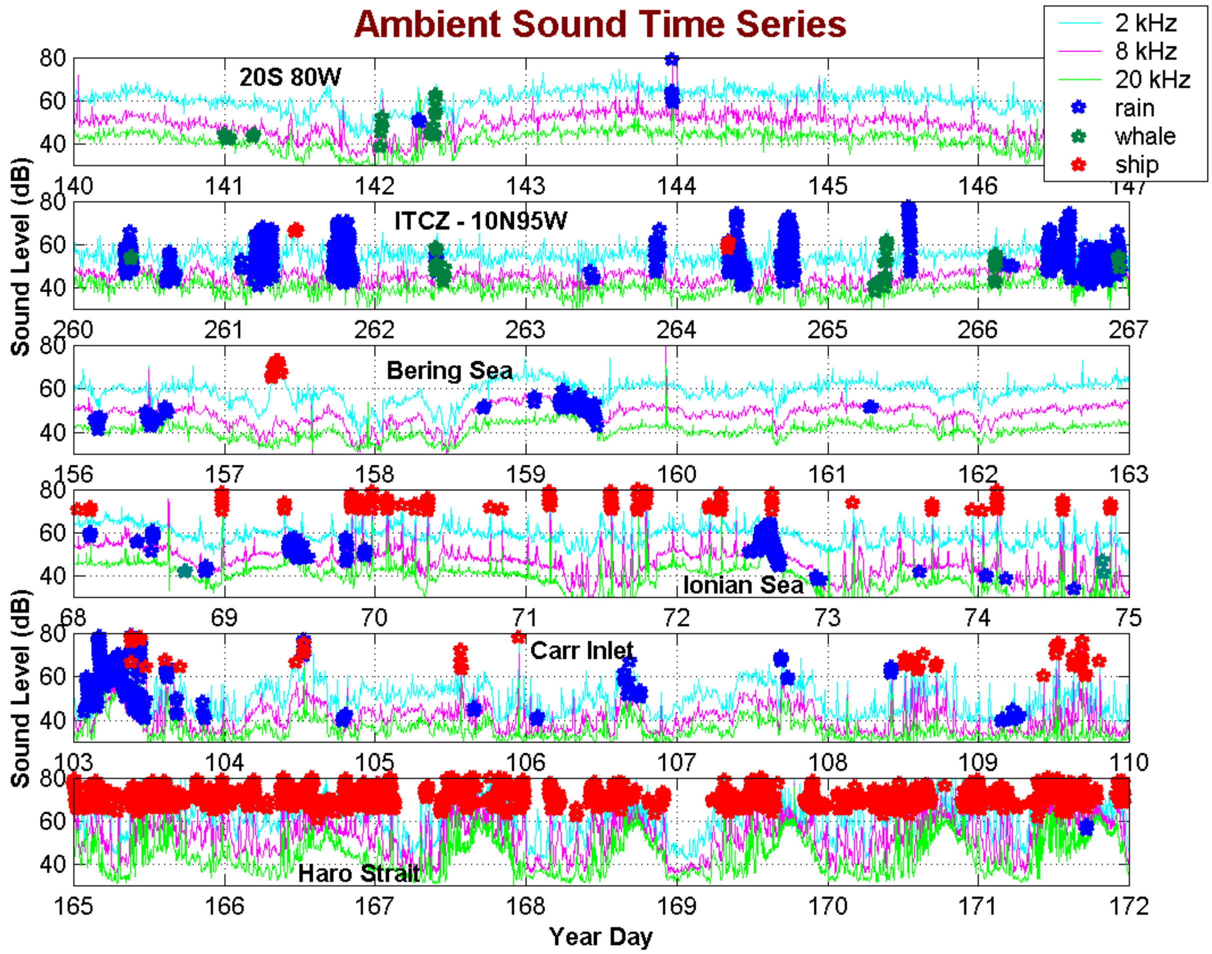


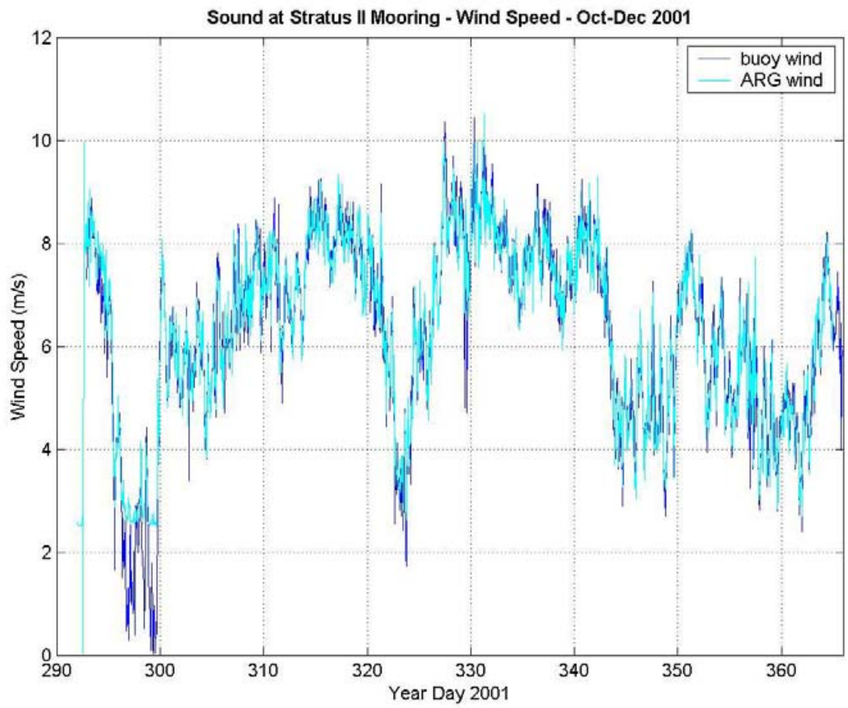
Figure 1. Week-long time series of underwater sound levels from 1) eastern South Pacific (20ºS,80ºW), 2) eastern Tropical Pacific (ITCZ 10ºN, 95ºW), 3) Bering Sea coastal shelf, 4) Ionian Sea, 5) Carr Inlet, Puget Sound, Washington, and 6) Haro Strait, Washington/BC. The sound levels are shown for 2, 8 and 20 kHz, and sound sources are identified (for wind, ship, whales and rain).

RESULTS

A series of week-long PAL data from 6 different regions around the world is shown in Fig. 1. These examples show the character of ambient sound in the ocean. Sound levels vary slowly over time, interspersed with loud events. The slow change over time is closely correlated with wind speed, that is, the sound associated with breaking waves. This is, in fact, a signal that can be used to quantify wind speed (Vagle et al. 1990). Validation of the acoustic wind speed measurement is shown in Fig. 2.

The short duration events that occur in the time series are also of interest. These are either natural sounds or anthropogenic sounds. In general, these other sounds have unique spectral characteristics that allow them to be detected and possibly quantified. Figure 3 shows the mean acoustic signature of wind and rain generated underwater sound. Wind is relatively quiet, with a constant spectral slope from about 0.5 kHz to over 20 kHz. Rain is relatively loud, with a relatively flat (white noise) spectrum from 2-10 kHz. And drizzle (light rain with few large raindrops) produces a loud peak in the sound field from 13-25 kHz. This is due to unique bubble formation mechanism for small raindrops

(Medwin et al.,1992; Nystuen, 1996). This allows rainfall to be detected and quantified using passive acoustic monitoring (Nystuen, 2001; Ma and Nystuen, 2005). Oceanic rainfall is a notoriously difficult quantity to measure, and yet is a basic component of sea state and ocean surface conditions.



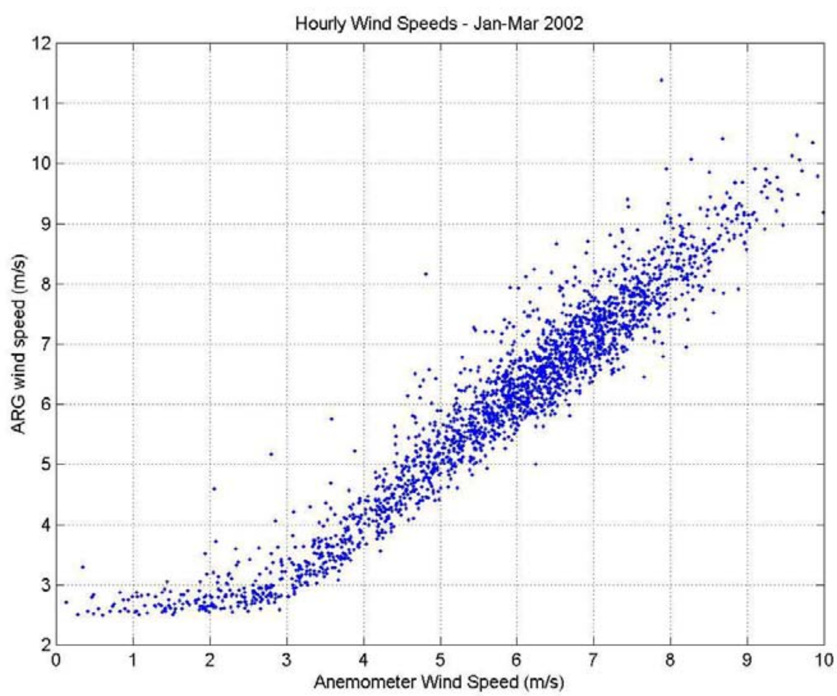


Figure 2. Comparison of acoustic wind speed measurements with a co-located physical anemometer at a deep ocean mooring in the eastern South Pacific Ocean (20ºS 80ºW).

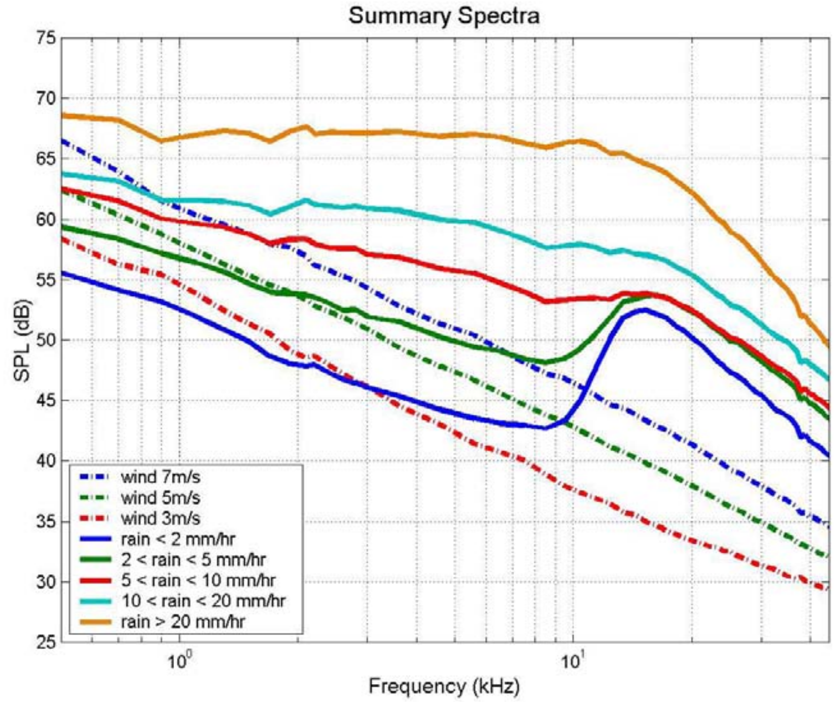


Figure 3. Mean underwater spectral signatures for wind and rain. Rain generated sound is relatively loud and has unique spectral features that allow it to be detected and quantified acoustically. The peak in the spectrum at 13-25 kHz during light rainfall is due to a bubble production mechanism by small raindrops. The effect of ambient bubbles is to depress the observed sound levels at high frequency.

While the sound generated by rain is generally much louder than wind-generated sound, there is an observed effect of wind on the rain-generated sound (Fig. 4). Ma et al. (2005) developed a model predicting the sound field given wind speed and rainfall rate. The inversion of this model, to estimate the wind speed and rainfall rate given the measured sound field will allow remote sea state measurements in conditions where surface instrumentation and even satellite measurements are unreliable.

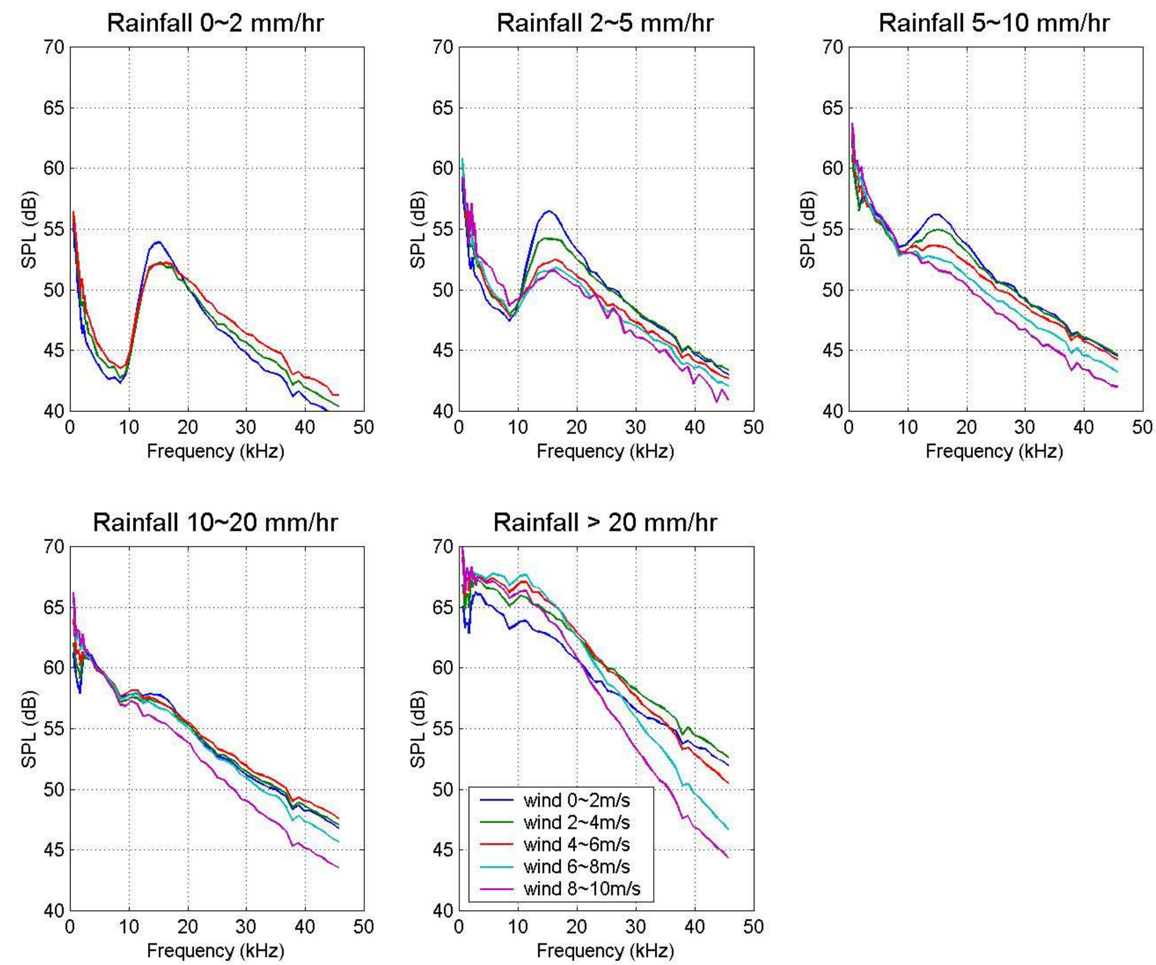


Fig 4. The influence of wind on the sound spectra generated by rainfall for different rainfall rates. This effect has been empirically modeled (Ma et al. 2005), thereby improving ambient noise prediction model for wind and rain.

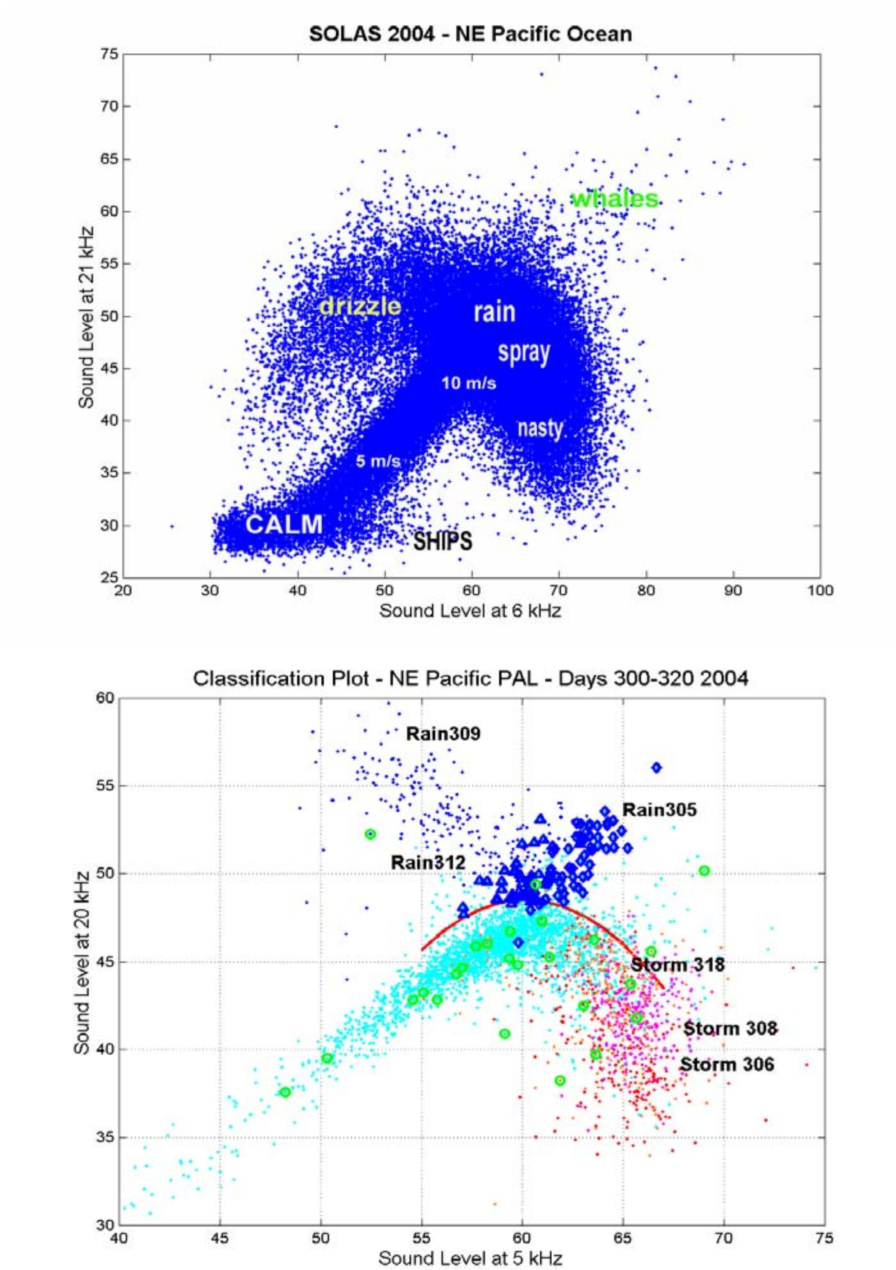


Fig 5. Scatter diagrams showing the relationship between the sound level at 8 and 20 kHz from the NE Pacific Ocean (50°N 145°W). By tracking individual rain and storm events, different parts of these scatter diagrams are associated with different sound sources.

The role of ambient bubbles in the surface layer is a particularly interesting subject. Bubbles are injected into the ocean surface by breaking waves and spray, as well as by rain, and produce distinctive sound that allows detection and quantitative measurement. But at very high sea states, these same bubbles are stirred down into the surface layer and absorb sound, changing the recorded sound field. Smaller bubbles are more easily mixed downward and absorb sound at higher resonant frequencies than the larger bubbles. Consequently, the effect of ambient bubbles is to depress the observed sound

levels at high frequency. This phenomenon is shown very dramatically in Fig. 5, a year-long record of the comparison of ambient sound levels at 6 and 21 kHz from the NE Pacific Ocean (50°N 145°W). By tracking individual storms and rain events, different parts of these scatter diagrams can be associated with different sound sources (e.g., calm, wind, drizzle, rain in wind, spray, very high winds, etc.).

Marine mammals are also responsible for generating sound in the ocean as they hunt and communicate with one another. The spectral signals for these sounds are usually unique and can be used to detect and monitor the animal populations. For example, at most deep water moorings where PALs have been deployed, a unique 30 kHz "click" is detected at irregular intervals throughout the deployment. The spectral character of this sound is shown in Figure 6. This sound is consistent with recent reports of the sound made by beaked whales (Johnson et al. 2004), although no "visual" observations are available to confirm the source of the sound. This type of whale is particularly difficult to track as they live in deep water locations and spend most of the time underwater. This is also the group of whales that are apparently particularly sensitive to disturbance from Naval sonars. Developing the ability to detect where and when these animals are present is thus particularly important for developing a decision aid for allowing sound producing activities, in particular, Naval operations and research activities, that might affect these animals. The new feature of the PAL data collection capacity should be particularly useful for identifying marine mammals. Fig 7. shows a 4.5 second time recording of an orca whale detected in Haro Strait between British Columbia and Washington. These time series will allow identification of sound sources and their spectral signatures, improving the objective classification algorithm needed to produce sound budgets.

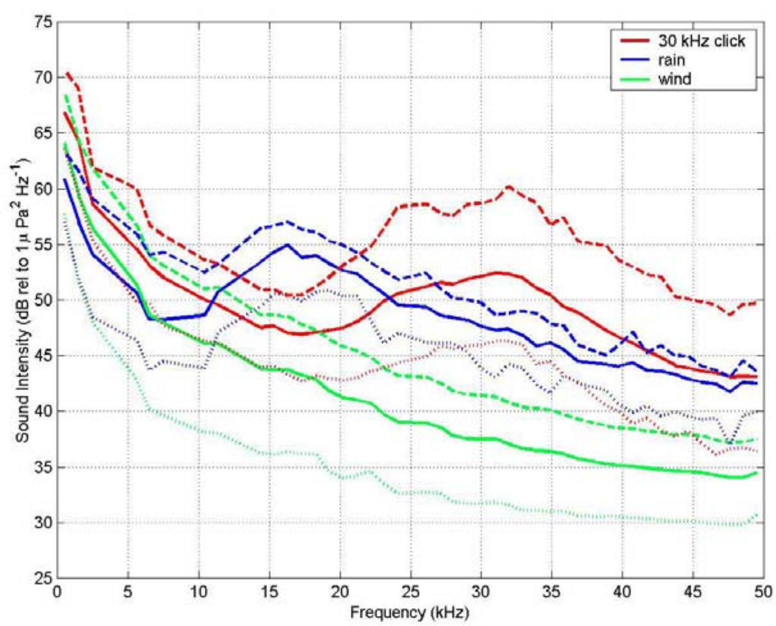


Figure 6. The spectral character of a 30-kHz "click" detected at a deep ocean mooring. The median spectra for wind, rain and the click are shown (solid lines) and the 5 and 95 percentiles are shown as dashed lines. The 30-kHz sound was detected about 80 times during a year-long deployment and lasted about 30 minutes per detection.

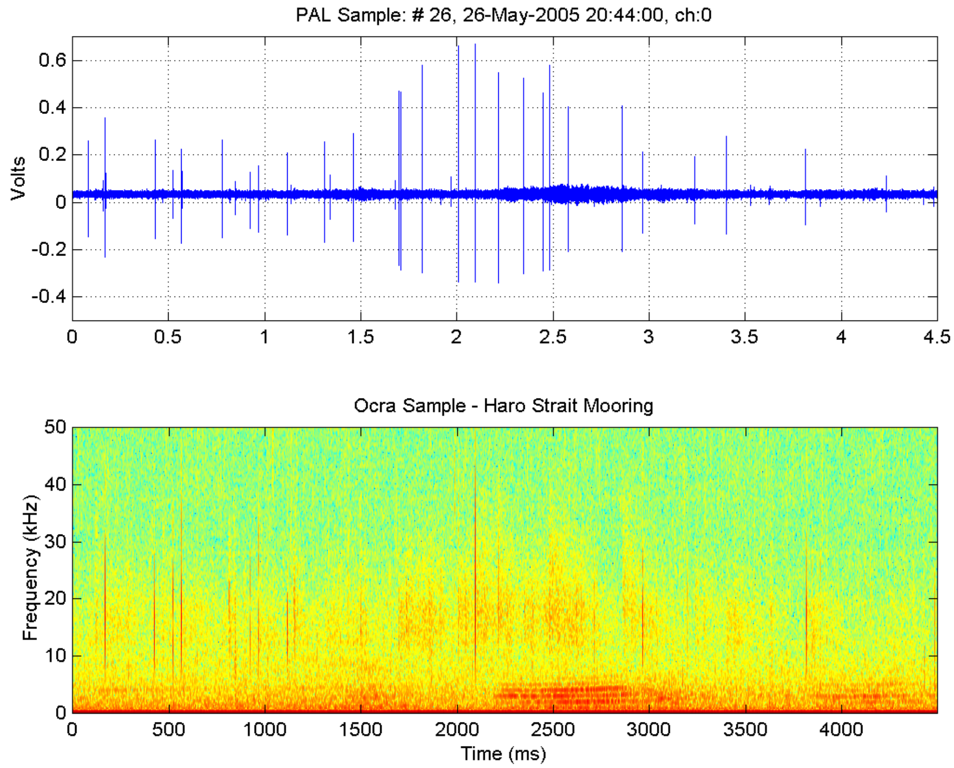
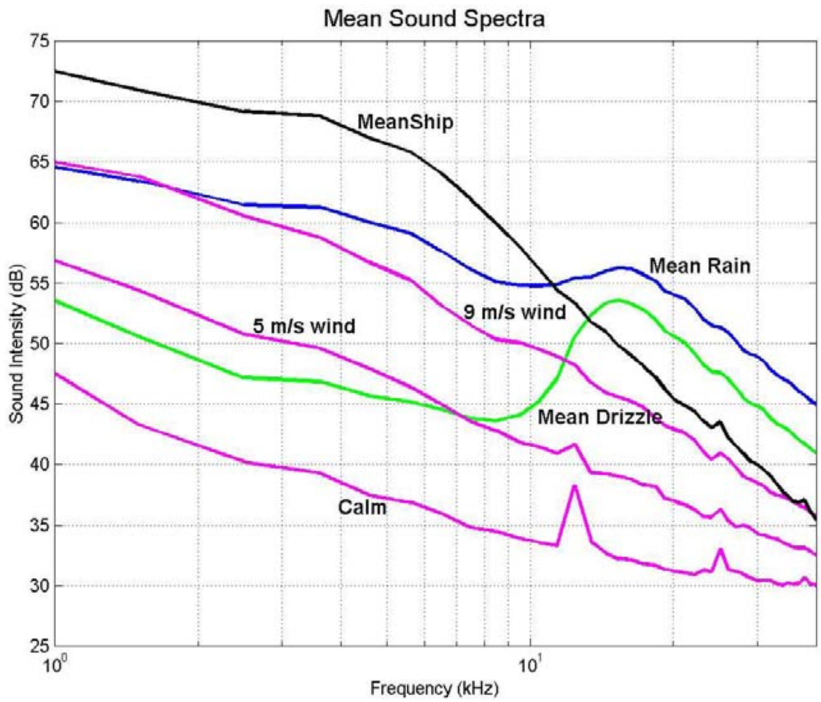


Figure 7. A 4.5-second time series collected in Haro Strait, May 26, 2005. The upper panel shows the time series, a series of clicks and a longer whistle. The lower panel shows the spectral decomposition of the time series. Several 20-kHz echo location clicks are present and the distinctive tonal whistle between 2-5 kHz (at time 2.2 sec). This has been identified as a Southern Resident Killer Whale (Puget Sound).

In coastal and inland waterways, anthropogenic noise is often present. These signals are usually transient, e.g., a passing ship, but can be quite loud and dominate the underwater sound field when they are present. The spectral characteristics of these sounds are variable, but again, distinctive, allowing passive detection and classification of the source. An example of the mean signal from a passing ship is shown in Fig. 8. Typically ships generate relatively more sound at lower frequencies than wind or rain.



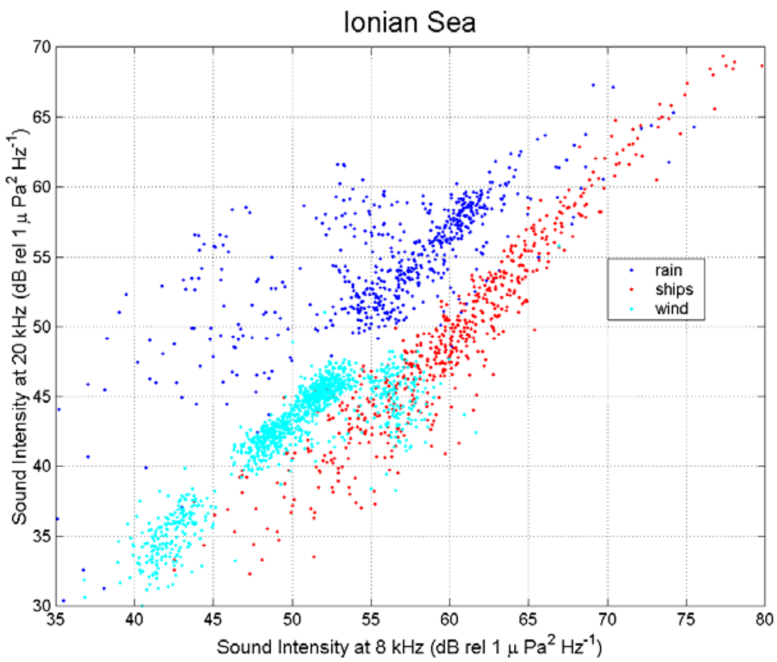


Figure 8. The mean sound spectrum for a ship is shown compared to the mean spectra from rain, drizzle and winds (calm, 5 m/s and 9 m/s) (top). When plotted on a scatter diagram (bottom), the signal from shipping contains relatively more low frequency sound and can be identified.

Ultimately a sound budget summarizes the acoustic characteristics of the given location. This is achieved using an objective identification algorithm to classify the sounds detected. The most useful characteristics are sound levels at selected frequencies, differences of sound levels between frequencies, and slopes of the spectrum within different frequency bands. Table 2 shows the sound budgets for the PAL data shown in Figure 1 as percentage of time that each sound source is dominant. Once sound sources are identified, the signal can be quantified and the relative loudness of the different sound sources can be compared.

Table 2. Sound budgets for the time series shown in Figure 1.

Dominant Sound Sources – Percentage of time present

	20 S 85 W	10 N 95 W	Bering Sea	Ionian Sea	Carr Inlet	Haro Strait
Wind	93%	86%	90%	74%	80 %	21 %
Rain	-	8 %	3 %	3 %	8 %	5 %
Ships	0.5 %	1.5 %	1 %	20 %	2 %	59 %
Whale*	1.8 %	0.6 %	-	0.5 %	-	-
Other	5 %	4 %	6 %	2 %	10 %	15 %

*30 kHz click detected – no visual confirmation

IMPACTS/APPLICATIONS

Ambient sound measurements are made from robust instruments at sub-surface locations. This implies a relative safe and covert method for obtaining useful sea surface condition measurements where surface moorings are unavailable or cannot survive. This includes ice-covered locations and other extreme weather conditions. The technology can be transferred to many other platforms including drifters, profilers, sea gliders, cabled systems and bottom moorings. Knowledge of the presence and identity of marine animals, especially whales, is important for monitoring their populations, but also will allow potential harmful human activities, in particular, the use of active mid-frequency sonars, to be mitigated in an informed way when animals are present. And having a baseline of sound budgets from a wide variety of marine environments will allow future decisions regarding the impact of proposed human activities, including Naval operations and research efforts, on those environments.

TRANSITIONS

An improved ambient noise prediction model for wind and rain has been published (Ma et al. 2005) and is available for incorporation into operational ambient noise models. Ambient noise is one of the basic components of predicting the performance of various Naval systems, including sonars, communications and weapon systems underwater.

The PAL technology has been installed on two different ocean instrumentation platforms: ARGO floats and Mixed Layer Floats. The ARGO project (NOPP sponsor) is demonstrated acoustic wind speed and rainfall measurements from a deep ocean float. The MLF application (ONR CBLAST sponsor) provides ambient sound measurements under extreme hurricane sea state conditions.

RELATED PROJECTS

"Spatial Averaging of Oceanic Rainfall Variability using Underwater Sound" sponsored by the National Science Foundation (NSF) Physical Oceanography Division. This project is investigating the inherent spatial averaging of the underwater acoustic rainfall signal associated with the depth of the measurements. Co-located high resolution coastal radar data are being compared to acoustical rainfall data collected at 60, 200, 1000 and 2000 m depths. This will allow PAL technology to be used on instrument platforms that are deployed at depth including deep-going ARGO floats and bottom-mounted systems.

"Marine Mammal Monitoring for NW Fisheries" sponsored by NOAA NW Fisheries Science Center (NWFSC). This project monitors the ambient sound field at highly active and noisy locations where marine mammals are present. The goal is to quantify the sound field and to demonstrate detection of specific marine mammals (Fig. 7). It has allowed a modification to the PAL operating software that enhances identification of underwater sound sources.

REFERENCES

Johnson, M, PT Madsen, WMX Zimmer, N Aguilar de Soto and PL Tyack, 2004: Beaked whales echolocate on prey. *Proc. R. Soc. London B (Suppl.)* DOI 10.1098/rsbl.2004.0208.

Ma, BB, JA Nystuen and RC Lien, 2005: Prediction of underwater sound levels from rain and wind. *J. Acoust. Soc. Am.* **117**, 3555-3565.

Ma, BB and JA Nystuen, 2005: Passive acoustic detection and measurement of rainfall at sea. *J.Atmos. and Oceanic Tech.* **22**, 1225-1248.

Medwin, H., JA Nystuen, PW Jacobus, LH Ostwald and DE Synder. 1992: The anatomy of underwater rain noise. *J. Acoust. Soc. Am.* **92**, 1613-1623.

Mellinger, DK, KM Stafford, SE Moore, L Munger and CG Fox, 2004: Detection of North Pacific right whale (*Eubalaena japonica)* calls in the Gulf of Alaska. *Marine Mammal Science* **20**, 872-879.

Nystuen, JA, 1996: Acoustical rainfall analysis: Rainfall drop size distribution using the underwater sound field. *J.Acoust. Soc. Am.* **13**, 74-84.

Nystuen, JA. 2001: Listening to raindrops from underwater: An acoustic disdrometer. *J. Atmos. and Oceanic Tech*. **18**, 1640-1657.

Vagle, S., WG Large and DM Farmer, 1990: An evaluation of the WOTAN technique for inferring oceanic wind from underwater sound. *J. Atmos. and Ocean. Tech.* **7**, 576-595.

PUBLICATIONS

Nystuen, J.A., 1997: Validation of Acoustic Measurements of Wind and Precipitation using Expendable Ambient Noise Sensor (ANS) Drifters, AN/WSQ-6 (XAN-2). Final Technical Report, Grant #N00014-94-1-G906, Naval Research Laboratory, via Defense Technical Information Center, Alexandria, VA 22304-6145, 21 p.

Nystuen, J.A. and H.D. Selsor, 1997: Weather Classification using Passive Acoustic Drifters. *J. Atmos. and Oceanic Tech*., **14**, 656-666.

Nystuen, JA, 1998: Temporal sampling requirements for autonomous rain gauges. *J. Atmos. Oceanic Tech.* **15**, 1254-1261.

Nystuen, J.A., 1999: Relative Performance of Automatic Rain Gauges under Different Rainfall Conditions. *J. Atmos. and Oceanic Tech*., **16**, 1025-1043.

Nystuen, J.A., 1999: Listening to Raindrops, *Solstice* **10**, Number 2, http://www.csfnet.org/image/solstice/win99/janystuen/listen.html

Nystuen, J.A., M.J. McPhaden and H.P. Freitag, 2000: Surface Measurements of Precipitation from an Ocean Mooring: The Underwater Acoustic Log from the South China Sea", *J. Applied Meteor*. **39**, 2182-2197.

Nystuen, J.A., 2001: Listening to Raindrops from Underwater: An Acoustic Disdrometer. *J. Atmos. and Oceanic Tech.* **18**, 1640-1657.

Nystuen, J.A. and E. Amitai, 2003: High Temporal Resolution of Extreme Rainfall Rate Variability and the Acoustic Classification of Rainfall. *J. Geophys. Res.*, **108** Number D8, 8378, doi:10.1029/2001JD001481.

Nystuen, J.A., 2005: Using Underwater Sound to Determine Drop Size Distribution. *Sounds in the Seas: Introduction to Acoustical Oceanography*, editor, H. Medwin, Cambridge Unversity Press.

Ma, B.B., J.A. Nystuen and R-C. Lien, 2005: Prediction of Underwater Sound Levels from Rain and Wind", *J. Acoust. Soc. Am.* **117**, 3555-3565.

Ma, B. and J.A. Nystuen, 2005: Passive Acoustic Detection and Measurement of Rainfall at Sea. *J. Atmos. and Oceanic Tech*. **22**, 1225-1248.

AWARDS and PRIZES

2003 Medwin Prize for Acoustical Oceanography by the Acoustical Society of America
"for the development of the theory for the acoustic detection and measurement of rainfall at sea"

2003 Elected Fellow, Acoustical Society of America